

INVESTIGATION OF PROCESS PARAMETERS AND PROCESSES FOR FABRICATION OF AL6061/SiC COMPOSITE BY FRICTION STIR PROCESSING FSP.

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DOI: <https://doi.org/10.5281/zenodo.23181951>

Keywords

Al6061/SiC composite, Friction stir processing, ANOVA, S/N Analysis, Taguchi Design Analysis, DOE

Article History

Received: 25 June 2026

Accepted: 16 September 2026

Published: 06 October 2026

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Abstract

Friction Stir Processing FSP is an eminent technique which promises modifying mechanical . To enhance the mechanical properties of Al-6061/SiC composite by investigating the influence of processes and process parameters was the objective of this research. Design of experiment DOE was applied to investigate influential parameters of composite prepared by FSP. These parameters were tool rotational speed, tool traverse speed, number of passes and tool direction of rotation. According to Taguchi Design, experimental data was collected and then analysis of variance ANOVA, linear model analysis and signal to noise ratio S/N analysis was carried out for investigation of relative significance of each parameters. The maximum UTS obtained from the test runs and at optimum parameters were 210.73 MPa and 213.05 MPa respectively which was in good agreement with the predicted values of Minitab 19 software.

INTRODUCTION

Friction stir processing FSP is a variant of friction stir welding process that is a solid-state processing technique and purpose of introducing this new technique is to improve selected mechanical properties of the base materials like tensile strength, toughness, hardness, wear resistance and fatigue. The main parameter is the heat generation due to the rotation of tool into the base material, and this heat causes the material to become soften and traverse motion cause the material to plasticized, while blending and mixing .The change of mechanical property in dependent on the grain refinement and homogeneity of the

grains under processing and this achieved by plasticizing the material below melting point thus creating ultrafine, homogeneous and equiaxed grain structure. This not only improves the mechanical properties but also improves many other manufacturing processes to be performed on the material like production of such metallic alloys which has more toughness than it can be achieved without the FSP. Also, special applications requires special surface properties like to improve instance surface wear resistance, surface hardness and surface corrosion resistance properties. For all the requirements and demand to be met, FSP is found to be the

best technique for such production and requirements. Friction stir processing was founded and headed by Mishra et al. [1, 2]. FSP is same like the working principle of friction stir welding in which the changes the property due to the microstructure changes of material. FSP has found wide acceptance in the field of growing material processing technique and its application in fabrication, processing, and synthesis of metallic materials is in accepted and implemented worldwide [3–5].

The most imperative processing parameters in friction stir processing are the tool rotational speed, traverse speed of the tool relative to base material, the geometry/design of the tool and pin and downward force. Other than these there are multiple other parameters as well like machining parameter, tool shoulder size, tool tilt angle, tool depth, reinforcement strategy, number of passes etc. These processing parameters imparts a great influence on the microstructure of the processed material. Some of these processing parameters are discussed here. The most important is tool rotational speed which clearly affects the properties of as processed material because of the development of the microstructure in friction stir processing zone. It directly affects the amount of grain refinement. It can be correlated with the temperature as for plasticizing, heat requirement depends on the rubbing of the tool with the material. The rotational speed of the tool should be greater in order to achieve higher temperature that results due to rubbing. The main advantage is that the tool rotational speed can easily be governed for the purpose of controlling the microstructure. In other words microstructure is controlled by the tool rotational speed. The rotational speed of tool is also an important processing variable that influences the degree of plasticity of the materials and to make the solid state stream of material in the processed material and grain refinement. Second most important parameter is the travelling speed of the tool along the surface of the material or in other words it is the linear speed of the rotating tool that travels

relative to the base material while friction stir processing. Both the variables, tool traverse speed and the tool rotational speed has a significant effect on the resultant developing properties of the material that is under FSP. The uncommon combination of higher traverse speed and lower rotational speed reflected a higher micro-hardness in the processed material [6]. This is very unusual as it is only for the micro hardness property, the right combination of both variables needs to be find out for required output properties and microstructures. The shape, size and geometry of the tool is another crucial process variable involved in friction stir processing as the two main functions of the tool is to make the material flow and to provide localized heating. Researchers have done numerous works with different tool geometry that clearly depicts that tool shape have a great impact on the evolving properties in FSP [7, 8]. Some of the tools like cylindrical tool, square tool, threaded tool and pin less tools have been used in FSP by the researchers that clearly portrays the resulting properties from their use. So these shapes of tools can be used on the materials depending upon the requirement of the microstructure. The heat that is produced is somehow dependent upon the downward force as it the force by which the rotating tool is brought in contact with the material surface. The force that is applied on the tool is responsible for friction between the material under processed and the tool which ultimately results in the generation of heat that is useful and prime principle of FSP. Therefore this downward force is one of the key variable for microstructural development in FSP. This force needs to be consistent throughout the process and it is desired to be controlled for best output of microstructure as well as mechanical properties [9]. FSP has a many leads and benefits and as it is widely used in a many industries. In the present work, effect of four parameters comprising tool rotational speed, tool traverse speed, number of passes and tool direction of rotation on UTS was investigated. Total 9 experiment runs were designed as per Taguchi L9 orthogonal array and

experimental data have been collected then analysis of variance ANOVA, linear model analysis and S/N analysis was carried out for

investigation of relative significance of each parameters affecting the mechanical behavior of the composite



Materials and methods

Experimental procedure

Commercially available AL-6061 alloy sheets of 6.5mm thickness and Silicon Carbide powder of approximately 36 microns were used as matrix and reinforcement respectively. Size of sample sheets were 150mm x 200mm x 6.5mm (width x length x thickness). The tool used was of H-13 tool steel material for preparing the pin less and tool having threaded pin (M6 x 1 thread type)

as threaded cylindrical pin gives optimum results for distribution of reinforcement particulates[10] , [11]. The diameter of pinless and tool having pins was set to 18mm and 22mm. Length of pin was selected as 5mm (about 76% of the plate thickness) having diameter of pin as 6mm [12]. Images of both pin and pin-less tool is shown Fig. 1 (a) and (b) respectively. Schematic diagram of tool having pin is shown in Fig. 1 (c).



Fig 1 a: Threaded pin tool

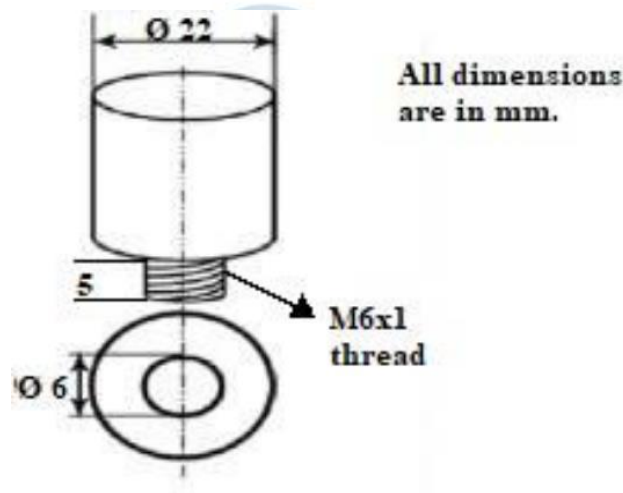


Fig 1 b: Pinless too

Fig 1 c: Illustrative diagram of tool having threaded pin

The sample sheets were first installed in horizontal milling machine and groove of dimension 1.2mm in width and 4.8mm in depth was machined by using circular saw cutter of 1mm x 100mm x 25mm specification. Then groove was initially washed with acetone to remove any surface impurity like traces of grease, oil, erosion, coolants, residue from cutoff blades and burned surface. Small amount of methanol (CH₃OH) was blended with SiC powder to formulate paste and then this paste was packed into the

groove by hand as used by S. Rathee et al. [13]. The sample plate then installed on vertical milling machine and fixed properly with vices. The top opening of the compacted groove was then initially closed by a pin less tool. After enclosing the SiC particles in groove, the FSP was applied on to the sample plate. Before performing FSP, tool was offset to 1.5mm away from the center of groove towards the retreating side so as to improve the mixing of reinforcements in base material [13] as this will gives better

homogeneity in reinforcement distribution. Tool was plunged at the rate of 4 mm/min [14] and tool plunge depth of 0.25mm was given. The rotating tool was dwelled for a short time period of 10 seconds [15] to preheat the material. Thus using the above mentioned parameters successful experiments were runs with great care and cautions. For observing the tensile property the tensile specimens (as per ASTM standard E8/E8M-11) were hauled out from the center of stir zone with the help of (EDM) CNC Wire Cutting machine [16]. Tensile tests were performed at a strain rate of 1 mm/min [11]. Two tensile samples were extracted from each sample plate, one parallel to the direction of stir line and one in the traverse direction of stir line.

Then average of both tensile specimens were calculated

2.2. Design of experiment (Taguchi L9 Orthogonal array)

Taguchi design of experiment DOE, is statistical approach of finding the best quality of product and process by reducing the variation through robust design of experiments. Minitab 17 software was used to generate Taguchi design of experiment. Tool rotational speed, tool traverse speed, number of passes and direction to tool rotation were taken as variables, while each variable has 3 levels except fourth variable direction of tool rotation which has only two levels as shown in table 1.

Table 1: Design variables with each level values

Design Variables	Level 1	Level 2	Level 3
Tool Rotational Speed (rpm)	670	950	1320
Tool Traverse Speed	17	24	33
Number of Passes	1	2	3
Rotation of Tool	Clockwise	Counterclockwise	-

Once the designated combination of variables were generated, then test runs were performed as per FSP procedures that is discussed in next heading and after experiment runs, testing is done and results were compiled and examined through Minitab software. Software showed the optimum levels of variables for each test. At the end these optimum variables were used in experiment test run to validate the results given by Minitab software.

Results and Discussions

The statistical analysis was done on Minitab 19 and data of tensile test runs were fed in Minitab 19 software for the purpose of analysis. According to signal to noise ratios SN-Ratio and means the results were interpreted by setting Larger is better as response output for signal to noise ratio and means as larger value of tensile strength is better. The tabulated data of UTS, SN-Ratio and means are shown table 2

Table 2: Taguchi DOE L9 orthogonal array with SN Ratio and Means

Experiment Run										
16										
17										
Tool Rotational Speed (rpm)										
Traverse Speed (mm/min)										
Number of passes										
Rotation of Tool										
Average UTS (MPa)										
S/N Ratio Means MPa										
1	670	17	1	CW	154.05	43.75	154.05			
670	24	2	CCW	168.2	44.51	168.2				
670	33	3	CCW	174.35	44.82	174.35				
950	17	2	CW	161.79	44.17	161.79				
950	24	3	CW	170.76	44.64	170.76				
950	33	1	CCW	179.76	45.09	179.76	46.06	201.02	201.02	

Here larger the better option is selected and the responses for SN-Ratios and Means of each levels of parameters are tabulated in table 3 and table 4 respectively.

Table 3: Response table for SN-Ratios of Al6061/SiC composite (Larger is better)

Levels	tool rotational speed (rpm)	Tool traverse speed (mm/min)	Number of passes	Direction of rotation tool
	44.37	44.71	44.93	44.92
	44.64	45.04	44.92	45.16
	46.08	45.33	45.23	-
	1.71	0.62	0.31	0.24
	1	2	3	4

Table 4: Response table for Means of Al6061/SiC composite

	tool rotational speed rpm	Tool traverse speed mm/min	Number of passes	Direction of rotation tool
	165.5	173.4	177.4	177.2
	170.8	179.1	177.0	181.7
Rank	1	2	3	4

The main effect plots for SN-Ratios and means are shown in the Fig 2. In order to study the effect of individual parameters that yields the best

composite prepared by the FSP process, a statistical tool known as ANOVA analysis of variance was executed. For this case the main

operation is ultimate tensile strength and the individual parameters are tool rotational speed, tool traverse speed, number of passes and direction of rotation of tool. Minitab 19 was

used to perform ANOVA analysis. To verify the impact of these parameters on the ultimate tensile strength. The individual parameters were selected

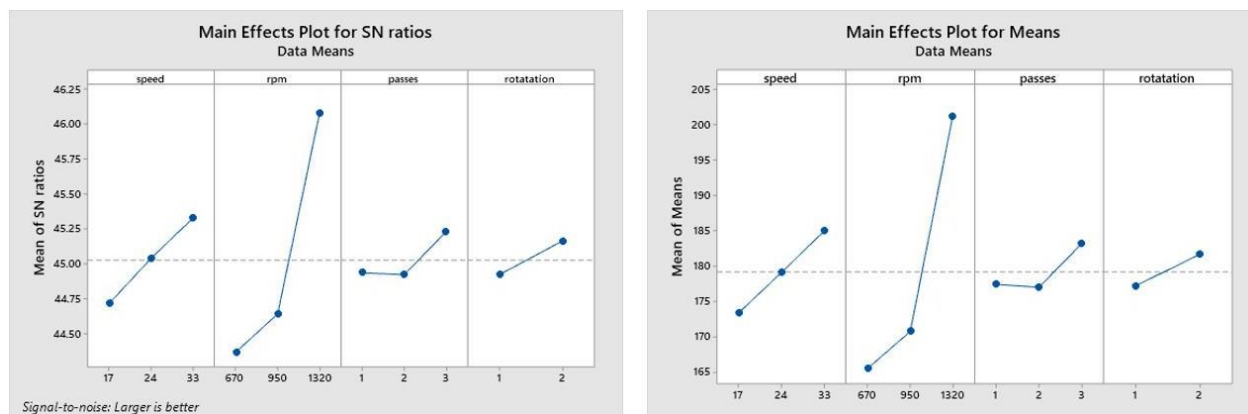


Fig 2: Main effect plots for SN ratios and Means obtained from Minitab

As the factors and the ultimate tensile strength was selected as the response. The ANOVA for

ultimate tensile is shown table in table 5.

Table 5: Analysis of variance for SN-ratios

Sr. No	Source	DF	Seq SS	Adj SS	Adj MS	F	P
1	Tool rotational speed	2	5.05669	5.36778	2.68388	380.34	0.036
2	Tool traverse speed	2	0.56916	0.32044	0.16022	6371.22	0.009
3	Number of passes	2	0.18173	0.04069	0.02035	48.30	0.101
4	Direction of rotation of tool	1	0.31177	0.31177	0.31177	740.10	0.023
5	Residual Error	1	0.00042	0.00042	0.00042		
6	Total	8	6.11976				

Percentage effect of factors (parameters) on the response (ultimate tensile strength) can be calculated via given equation 1 (by ROY R) given below [17] Seq SS= the pure sum of squares for individual factor Total SS= the total mean of sequential sum of squares. Here the calculation

for each individual parameter contribution percentage is done given below. Also the contribution is displayed on the pie chart given in Fig 3.

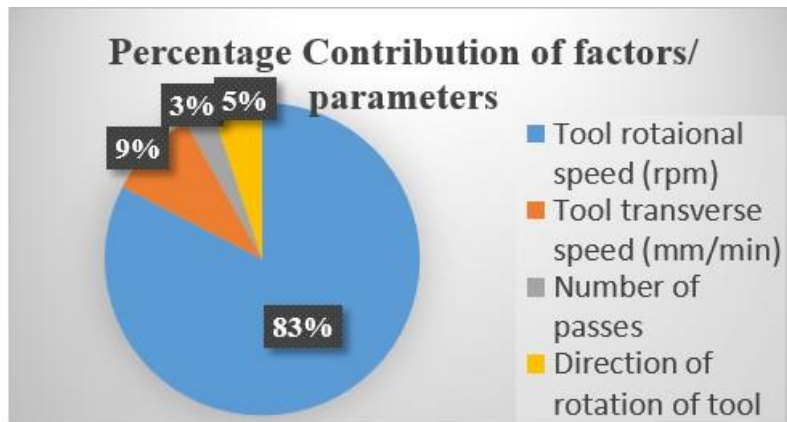


Fig 3: Percentage contribution of parameters

Percentage contribution for tool rotational speed (rpm) = $5.05669 / 6.11976 = 82.62\%$ Percentage contribution for tool traverse speed = $0.56916 / 6.11976 = 9.3\%$ Percentage contribution for number of passes = $0.18167 / 6.11930 = 2.96\%$ Percentage contribution for direction of rotation of tool = $0.31177 / 6.11930 = 5.09\%$ Percentage contribution error = $0.00042 / 6.11930 = 0.0068\%$ (negligible) Regression equation for ultimate tensile strength given by the analysis done by Minitab 19 is given by equation 2. $UTS = 89.0 + 0.493 \times \text{tool traverse speed} + 0.06164 \times \text{tool rotational speed} + 1.08 \times \text{number of passes} +$

$10.71 \times \text{direction of rotation of tool}$ (2) ($R^2 = 94.26\%$) Coefficients of regression equation are given in table 6 and analysis of variance for regression equation is given in table 7. The analysis showed that the best predicted set of optimal parameters are tool rotational speed of 1320 rpm, tool traverse speed of 33 mm/min, total 3 number of passes and counterclockwise rotation of tool according to the above SN-ratio and mean data graphs. Also the Minitab 19 predicted that at these set of parameters the SN-ratio will be 46.6775 and the mean will be 213.054.

Table 6 Coefficients of Regression equation

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	89.0	13.0	6.82	0.002	
tool rotational speed	0.06164	0.00802	7.68	0.002	1.09
tool traverse speed	0.493	0.329	1.50	0.208	1.10
number of passes	1.08	2.63	0.41	0.702	1.10
Direction of rotation of tool	10.71	4.68	2.29	0.084	1.29

Table 7 Analysis of variance for empirical modeling

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	2480.76	620.19	16.43	0.010
tool rotational speed	1	2228.39	2228.39	59.02	0.002
tool traverse speed	1	84.97	84.97	2.25	0.208
number of passes	1	6.39	6.39	0.17	0.702
Direction of rotation of tool	1	198.03	198.03	5.24	0.084

It can be clearly stated by observing Fig. 2 (the mean effect plots for SN-Ratios and Means) and Table 6 and table 7 (Response tables for SN-Ratios and means) that the optimal parameters to be tool rotational speed at level 3 (1320 rpm),

tool traverse speed at level 3(33 mm/min), number of passes at level 3 (3 passes) and direction of rotation of tool at level 2 (anticlockwise rotation of tool). Optimum parameters are summarized in the table 8 shown below. 5

Table 8: Optimum parameters

Tool rotational speed			
Tool traverse speed	Number of passes	Direction of rotation of tool	
1320 rpm	33 mm/min	3 passes	Anticlockwise

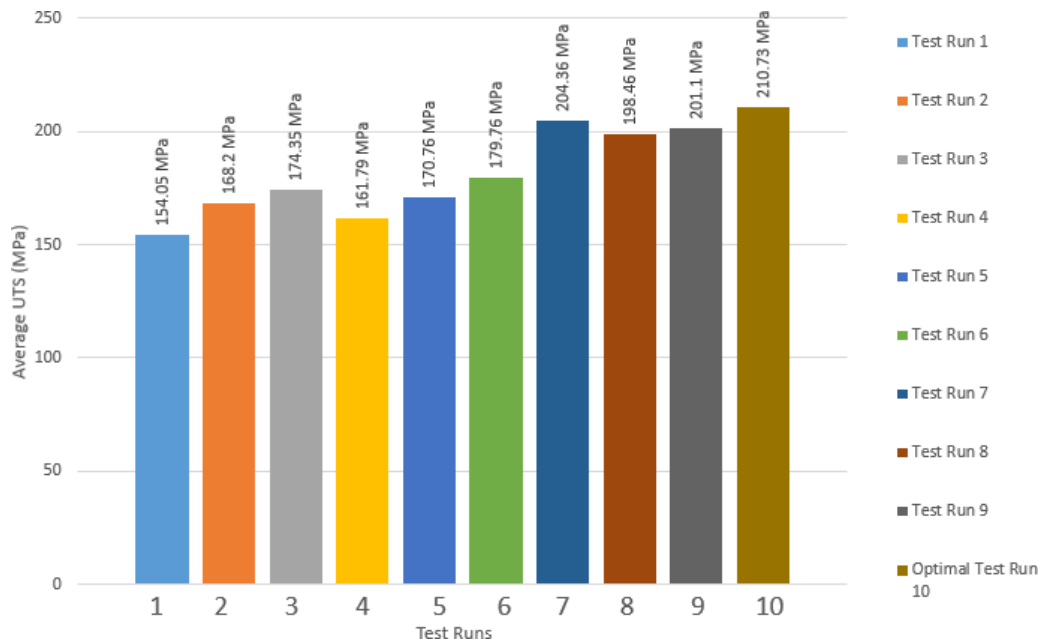


Fig 4: Summary of UTS results of all test runs

For experimental validation of optimum parameters for UTS, the FSP procedure was executed by setting the optimal parameters. The

validation of optimum results of UTS are summarized in table 9 as shown below. The summary of results are shown in Fig 4

Table 9: Validation of Optimum results

Sr.	
No	
Quality characteristics	
Optimum parameters	Theoretical
Optimum value of	
Experimental optimum value of UTS	

1	Ultimate tensile strength	1320 rpm, 33 mm/min,
3 passes,		
counterclockwise		
213.054 MPa	210.73 MPa	
	direction of tool	

These results clearly portrays that higher rotational speed confirms the proper heat generation which results in softening, mixing and plasticized flow of the material. The high tool rotational speed results enhanced microstructure growth and development which endorses the defect free processing region. An important observation is that if the number of passes is increased then the tensile property is little dependent on the traverse speed as the difference in the above mentioned average ultimate tensile values (173 MPa at 17 mm/min, 179 MPa at 24 mm/min, 184.6 MPa at 33 mm/min) at different traverse speeds are very little (about 2-3%). The reason is obvious that the defects and improper mixing caused by high traverse speed is catered by the next succeeding pass as the tool again stirs the material and breaks down any cluster present due to preceding pass. In short it is very clear from the results that tool traverse speed and number of passes have direct relation. For low tool traverse speed the number of passes has to be

decreased and vice versa. In this work, due to setting of variable tool rotational speeds and tool traverse speeds, the number of passes have least contribution of only 2.96 % in determining the eminence of ultimate tensile strength. Because in single pass FSP the tool traverse speed needs to be lower for defect free mixing and for stirring by contacting maximum time, but in multiple pass FSP the tool traverse speed can be set at higher values. The reason is obvious that each succeeding pass of the tool will stirs the material and breaks down any cluster present due to high traverse speed. Hence it is clear argument that for minimizing the number of passes the, traverse

speed should be minimized and vice versa.

Conclusions

It is concluded that successful fabrication of Al-6061/SiC was done and it came out that tool

rotational speed is the only outshined factor among all other factors. The maximum UTS obtained from the optimal test run and at optimum parameters by Minitab Software are 210.73 MPa and 213.054 MPa respectively. The parameters set in this research yields better UTS than existing literature papers by M. Salehi et al. [10] and A. Kumar [18]. The maximum ultimate tensile strength found by M. Salehi and A. Kumar were MPa and 203.5 MPa respectively. The experimental and depicted work values are better than existing literature work mainly due to two reasons (a) the increased tool rotational speed (b) increased number of passes. The optimal parameters found in this research work are tool rotational speed at level 3 (1320 rpm), tool traverse speed at level 3 (33 mm/min), number of passes at level 3 (3 passes), direction of rotation of tool at level 2 (counterclockwise direction). The lower tool traverse speed causes the lower distribution of reinforcement particles, so this effect can be controlled by changing the number of passes. Multiple passes allows the unmixed particles to mix well in the stir zone so the clustering issue can be addressed my multiple passes and thus causing to decrease the grain size. The optimal experimental value of UTS at optimal parameters were found to be in good agreement with the predicted value by Minitab 19 software.

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Cover letter

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COVER LETTER

[Dated: September 21, 2022]

Respected Sir/ Madam,

I am writing to express my interest to submit my research work in your high rated journal JMR. I hereby enclosed my manuscript for your kind consideration for submission. As I have done Mechanical Engineering Degree in 2015 and MS degree is recently completed in 2021. I have more than 5 years of teaching experience (2016-2022) with 1 year of field experience.

As novelty of FSP technique for fabrication is gaining attention so the objective of this research was to enhance the mechanical properties of Al-6061/SiC composite by investigating the influence of processes and process parameters. Both experimental and analytical study was done and presented in the manuscript.

I would be very grateful to you for your kind consideration and kind response.

Yours sincerely

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